Fundamental Research on Non-monotonic Reasoning(非単調推論に関する基礎的研究)

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論　文　内　容　要　旨

CHAPTER 1. INTRODUCTION

This chapter is the introduction in which the research background, motives and objectives are described in brief.

Logic of non-monotonic reasoning is an area of growing significance to artificial intelligence. Many researches have been made towards developing the logic with non-monotonic reasoning. Especially, McCarthy s circumscription and Reiter's default logic turn out to be influential formalisms which attempts to characterize non-monotonic reasoning.

Default reasoning corresponds to the process of deriving conclusions based upon patterns of inference of the form "in the absence of any information to the contrary, assume...". *Circumscription* suggests that the objects that can be shown to have a certain property by reasoning from certain facts are all objects satisfying this property.

CHAPTER 2. NON-MONOTONIC REASONING AND KNOWLEDGE BASE

Several formalisms of non-monotonic reasoning are formally reviewed. Some useful prelimi nary notations, important definitions and relative results are given in this chapter.

A *default* δ is an expression of the form $a(x)$:M$\beta(x)/\gamma(x)$, read as:if $a(x)$ is true and it is consistent to assume $\beta(x)$, then infer $\gamma(x)$, where $a(x)$, $\beta(x)$ and $\gamma(x)$ are first order formulas whose free variables are in $x = \{x_1,\cdots,x_n\}$. A *default theory* Δ is a pair (D, W), where D is a set of defaults and W a set of formulas.

Definition 2.3 Let $\Delta=(D, W)$ be a closed default theory and E a set of formulas. Define

(1) $E^{(0)}=W$;

(2) $E^{(i+1)}=\mathrm{Th}(E^{(i)})\cup\{\gamma \mid a{:}M\beta/\gamma\in D,$ where $a\in E^{(i)}$ and $\neg\beta\notin E\}$.

E is an *extension* for Δ *iff* $E=\cup_{i\geq 0}E^{(i)}$. GD (E) is the set of *generation defaults wrt E*, defined as:

GD $(E)=\{\delta \mid \delta=a{:}M\beta/\gamma\in D,$ where $a\in E$ and $\neg\beta\notin E\}$. □

Let $P=\{p_1,\cdots,p_n\}$ and $Z=\{z_1,\cdots,z_m\}$ be disjoint sets of predicate symbols.
Suppose $T(P,Z)$ is a first order sentence containing predicate symbols in P and Z.
The process of circumscription of P in $T(P,Z)$ with parameter Z, transforms $T(P,Z)$ into a sentence Circum$(T;P;Z)$ defined below.

Definition 2.5 The *circumscription* of P in $T(P,Z)$ with parameter Z is the following sentence, denoted by Circum$(T;P;Z)$:

$(T;P;Z)$ and for every P', Z' [if $T(P', Z)$ and $P'\Rightarrow P$, then $P\Rightarrow P'$],

where $P'=\{p_1',\cdots,p_n'\}$ and $Z'=\{z_1',\cdots,z_m'\}$ are disjoint sets of predicate variables similar to P and Z, respectively. $T(P',Z')$ is the result of $T(P,Z)$ substituting p_i' and z_j' for each occurrence of p_i and z_j, $1\leq i\leq n$ and $1\leq j\leq m$. $P'\Rightarrow P$ stands for $p_i'\supset p_i$, for every tuple of object variable x and for every i, $1\leq i\leq n$, □

CHAPTER 3. SEMANTICS OF DEFAULTLOGIC

The concept of default reasoning is defined proof theoretically by Reiter. Its model-theoretical issue remains to be discussed. In this chapter, a new concept of models for default theories will be introduced. Default logic will be observed from the viewpoint of model-theoretical semantics. We get an interesting result that, for a default theory in which the justification of every default contains only negative literals, it has a consistent extension if and only if it has a model.

Definition 3.1 Let $\Delta=(D, W)$ be a clausal default theory, M_0 any model of W and £ the set of all clauses in first-order logic.

(1) $\Gamma_0[M_0]=W$;

(2.1) $\Gamma_{i+1}[M_0]=\mathrm{Th}(\Gamma_i[M_0])\cup\{\gamma \mid a{:}M\beta/\gamma\in D,\ a\in\Gamma_i[M_0],\ M_0\not\models\neg\beta,$ and $M_0\models\gamma\}$;

(2.2) $\Gamma_{i+1}[M_0]=$ £, if for some $a{:}M\beta/\gamma\in D$, $a\in\Gamma_i[M_0]$, $M_0\not\models\neg\beta$, and $M_0\not\models\gamma$.

Then $\Gamma_\infty[M_0]$ is defined as: $\Gamma_\infty[M_0]=\cup_{i\geq 0}\Gamma_i[M_0]$. □

Definition 3.2 Let $\Delta=(D, W)$ be a clausal default theory in which the justification of every default contains no positive literals.

A model M_0 of W is a *model* of Δ *iff* $\Gamma_\infty[M_0] \neq$ £, and M_0 is a model of $\Gamma_\infty[M_0]$ minimal in JUST(D), the set of all predicate symbols occurring in the justification β of every default a:Mβ/γ in D. □

Theorem 3.1 *Let $\Delta=(D, W)$ be a clausal default theory, in which the justification of every default in D contains no positive literal.*

Then Δ has a consistent extension iff it has a model. □

CHAPTER 4. CIRCUMSCRIPTION

This chapter comprises two parts of : (1) computation of circumscription : and (2) generalized predicate completion and its relation to circumscription.

COMPUTATION OF CIRCUMSCRIPTION

Circumscription of a first-order sentence is generally a second-order sentence. How to mechanically carry out circumscriptive inference turns out to be a problem. However, for the first-order sentences under certain conditions, they have indeed first-order circumscriptions. *Separability* proposed by Lifchitz is one of those conditions. Independent of the separability, we have another sufficient condition shown as below.

Theorem 4.1 *Let p be an n-ary predicate symbol. If T is a finite function-free Horn clausal theory, then T has always first-order circumscriprion which is a theory of T augmented by τ_n and equality axioms* (E1),…,(E8),

$$\tau_n=\forall X.[p(X)\equiv \exists y_1.((X=t_1)\wedge p(t_1))\vee\cdots\vee\exists y_v.((X=t_v)\wedge p(t_v))]$$

where $X=<x_1,\cdots,x_n>, t_i=<t_{i1},\cdots,t_{in}>$ and $y_i=<y_{i1},\cdots,y_{im_i}>$. $X=t_i$ means $x_j=t_{ij}$ for each $1\leqq j\leqq n$. All p-atoms derivable from T are $p(t_1),\cdots,p(t_v)$. y_{ik}'s in y_i are variables appearing in t_i. □

GENERALIZED PREDICATE COMPLETION

Prior to McCarthy's circumscription, Reiter has proposed the *closed world assumption*(CWA), which says that the implicit representation of negative facts presumes total knowledge. CWA can efficiently be implemented via Clark's *negation as failure,* which declares that the negation of a proposition can be inferred if each of its possible proofs fails. Furthermore, that can be proved with negation as failure inference rule from a clausal sentence is a logical consequence of the predicate completion of this sentence. *Predicate completion* simply states that the given sufficient conditions on a predicate are also necessary.

As pointed out by Reiter that for clausal sentences which are Horn in a predicate p, Clark's predicate completion is implied by McCarthy's circumsription. Clearly, the completion is a non-trivial logical consequence of circumscription. That predicate completion is subsumed by circumscription for a wide class of clausal sentences is of some theoretical and computational interests. As mentioned by Reiter, before invoking the full power of circumscription, one should first try reasoning with predicate completion. In our opinion, this seems to be wise compromise.

From these points of view, we enlarge the class of first-order clausal sentences for which predicate completion can be subsumed by circumscription. We present a generalized completion of a predicate p, which refines on the definition of Clark's predicate completion. The generalized predicate cpmpletion is appropriate for clausal sentences which are not Horn in p. Reiter's result mentioned above is covered by our results.

The *generalized predicate conpletion of p* in T is the sentence T along with the necessary condition of the definition of p in T and the equality axioms, denoted as:

$\mathrm{Comp}_G(T;p) \equiv \{T, \forall x.[p(x) \supset E], (\mathrm{E1}), \cdots, (\mathrm{E8})\}$.

Let C be a clause, p a predicate symbol and T a clausal sentence.

Definition 4.1 C is *non-overlapping wrt p iff* for any distinct positive literals P and P' on p in C, P is not unifiable with P'. If every clause in T is non-overlapping *wrt p*, T is said to be *non-overlapping wrt p.* □

Theorem 4.3 *If T is non−overlapping wrt P then* $\mathrm{Circum}(T;p) \models \mathrm{Comp}_G(T;p)$, *i.e., the generalized completion of p in T is implied by the circumscription of p in T.* □

Definition 4.2 T is *collapsible wrt p* if it consists of:

(1) clauses containing no positive occurrences of p;

(2) clauses containing no negative occurrences of p. □

Theorem 4.4 *If T is non-overlapping and collapsible wrt p, then* $\mathrm{Th}(\mathrm{Comp}_G(T;p)) = \mathrm{Th}(\mathrm{Circum}(T;p))$, *i.e., the generalized completion of p in T is logically equivalent to the circumscription of p in T.* □

CHAPTER 5. A PARTIAL TRANSLATION OF DEFAULT THEORIES TO CIRCUMSCRIPTIVE DESCRIPTIONS

Default logic and circumscription have been proposed to formalize non-monotonic reasoning in the absence of complete knowledge. Both systems attempt to capture a similar phenomena, very little has been done to explore the relationship between them. A natural question is "how the two approaches are related each other".

In our opinion, maximizing the possibility of a proposition expected to hold (this is the approach in default logic) is similar to minimizing the possibility of propositions against this proposition (this is the approach in circumscription).

We limit ourselves to an open default of the form, $\alpha(x):M\beta(x)/\gamma(x)$, whose justification $\beta(x)$ contains no positive occurrences of a predicate. A partial translation of default logic to circumscription is proposed. And we show that, under certain conditions, for a given default theory, any consistent extension is a logical consequence of the resulting circumscription.

By $F[p^+]$($F[p^-]$), we mean F is a quantifier-free formula containing some *positive* (*negative*) *occurrences* of atomic formulas on a predicate symbol p. By $F[p^+;q^-]$, we mean F is a formula containing some positive occurrences of atomic formulas on p and some negative occurrences of atomic formulas on q.

Definition 5.1 Let T be a quantifier-free theory, *i.e.*, a set of quantifier-free formulas, and P a set of predicate symbols. Define a set $\mathrm{R}(T;P)$ of *oriented predicate symbols* as the least set satisfying the following rules:

(0) $p^{\downarrow}\in\mathrm{R}(T;P)$, for every $p\in P$;

(1) $r^{\downarrow}\in\mathrm{R}(T;P)$, if there is either a formula $F[q^+;r^-]$ in T for some $q^{\downarrow}\in\mathrm{R}(T;P)$; or $F[q^-;r^-]$ in T for some $q^{\uparrow}\in\mathrm{R}(T;P)$;

(2) $r^{\uparrow}\in\mathrm{R}(T;P)$, if there is either a formula $F[q^+;r^+]$ in T for some $q^{\downarrow}\in\mathrm{R}(T;P)$; or $F[q^-;r^+]$ in T for some $q^{\uparrow}\in\mathrm{R}(T;P)$.

Define the set $Z(T;P)$ of predicate symbols:

$Z(T;P) = \{q \mid q\notin p \text{ and } q^{\downarrow}\in\mathrm{R}(T;P) \text{ (or } q^{\uparrow}\in\mathrm{R}(T;P))\}$ □

Definition 5.3 Let $\Delta=(D,W)$ be an open quantifier-free default theory. The *translation* of Δ is defined as a quantifier-free theory Trans (Δ),

Trans $(\Delta)=W\cup\{\alpha(x)\wedge\beta(x)\supset\gamma(x) \mid \alpha(x):\mathrm{M}\beta(x)/\gamma(x)\in D\}$. □

Theorem 5.1 *Let $\Delta=(D,W)$ be a (an open) quantifier-free default theory and E a consistent extension for Δ.* Let $\Delta'=(\mathrm{GD}(E), \mathrm{INST}(W))$ *and* $Z=Z(\mathrm{Trans}(\Delta');\mathrm{JUST}(\mathrm{GD}(E)))$. *If*

(1) *every default in* GD(E) *contains only negative occurrences of predicate symbols in its justification; and*

(2) *Trans*(Δ') *is directional wrt* JUST(GD(E))

then Circum (Trans (Δ');JUST(GD(E));Z) $\models E$. □

CHAPTER 6. KNOWLEDGE BASE WITH NON-MONOTONIC REASONING

We make a draft of system which supports the knowledge bases with non-monotonic reasoning.

CHAPTER 7. CONCLUSIONS

This chapter contains the general conclusions.

審　査　結　果　の　要　旨

情報化社会の急速な発展に伴い，新しい情報処理の研究が望まれている。特に知識処理の分野では，従来の完全な知識に基づく推論とは異なる新しい推論の研究および知識ベースシステムの研究が重要となってきた。このような背景から，非単調論理による常識推論の研究が盛んに行なわれている。本論文では，非単調論理の分野で提案されているデフォールト論理（Default Logic）とサーカムスクリープション（Circumscription）の関係を明らかにする研究を行なった。本論文はその成果をまとめたもので，全編７章より成る。

第１章は序論である。

第２章では，テフォールト論理とサーカムスクリプション，並びにこれらに関連した諸概念についての定義を与えている。

第３章では，デフォールト理論のモデルを提案し，デフォールト理論のモデルを提案し，デフォールト理論から推論可能な信念の集合のクラスとモデルのクラスとの間には，ある条件の下で一対一の対応関係があることを述べている。これは，デフォールト論理の意味論を明確にする興味深い試みである。

第４章では，サーカムスクリプションの計算方法について研究している。前半で，高次推論であるサーカムスクリプションを１階述語論理に完全に帰着させるための十分条件を与え，１階述語論理での具体的な表現方法を論じている。後半では，一般のサーカムスクリプションを対象に，１階述語論理の枠組みに変換する方法とその健全性，および完全性が成り立つクラスについて論じている。

第５章では，デフォールト論理とサーカムスクリプションの相互関係について研究している。まず前半で，デフォールト理論をサーカムスクリプションに変換する方法を示し，デフォールト推論がサーカムスクリプションのモデル論に帰着可能であることをのべている。後半では逆に，サーカムスクリプションからデフォールト理論に変換する方法について述べ，サーカムスクリプションでの推論を第３章で展開したデフォールト理論のモデル論に帰着する問題を論じている。

第６章では，以上の成果に基づいて，不完全な知識を対象とした知識獲得と高次推論を定式化し，デフォールト推論とサーカムスクリプションに基づく推論による知識ベースシステム構築のための指針を与えている。

第７章は結論である。

以上要するに本論文は，今後の知識情報工学における重要な分野である非単調推論について研究し，その理論的基礎を明らかにしたもので，情報工学の発展に寄与するところが少なくない。

よって，本論文は工学博士の学位論文として合格と認める。